Reliability and Scalability of Wireless Kilavi Building Control Platform

MIKAEL SOINI, LAURI SYDANHEIMO, MARKKU KIVIKOSKI
Electronics Institute, Rauma Research Unit
Tampere University of Technology
Kalliokatu 2, 26100 Rauma
FINLAND

Abstract: - Building is a harsh environment for reliable wireless communication and thus special means are needed for wireless sensor networking. This paper presents Kilavi wireless building control platform that provides a unified method to link up different kinds of building control applications. Kilavi platform is intended for low-power and low data rate autonomous communication between sensors and actuators. Network master with plenty of storage and computation capacity manages network routing, cluster formation and security procedures. This centralized approach shifts network load away from simple and resource-constrained sensor and actuator nodes, thus enabling low power sensor node operation.
Sensor network offers the ambient intelligence to integrated building. Network reliability and scalability together with energy-efficiency and flexibility are amongst the primary qualities that sensor network platform should offer to applications. This paper concentrates on reliability and scalability of Kilavi in variable network topologies and conditions.

Key-Words: - Building control, Intelligent building, Kilavi platform, Middleware, Reliability, Scalability, Sensor networks, Wireless communication

1 Introduction

Recent advances in electronics have made wireless sensor networks viable. Sensor networks are based on physically small sensor nodes exchanging mainly environment related information with each other. Sensors usually have very limited power, processing, and memory resources, thus interactions between nodes are limited to very short distances and low data rates. Sensor networks can be used, for example, in wild life monitoring, forest fire detection, structure and health monitoring, industrial sensing, and home control. Home and building applications are among the most interesting and feasible ones in this field.

Wireless approaches bring flexibility to building automation. However, building is an intricate environment for wireless networking. This is due to strong and hard-to-predict radio wave propagation path loss that depends heavily on construction structures and materials, and communication frequency [1, 2]. ISM (Industrial, Scientific, Medical) bands such as 433MHz and 2,4GHz can be used for sensor networking. The used 433MHz frequency is especially suitable for low data rate control applications. With 433MHz, the propagation path loss is lower and number of channel users is smaller compared to 2,4GHz. This enables lower transmission power and decreased amount of interference.

Further, though sensors usually have low mobility, there can be changes in network topology caused by varying floor plans, furniture placements etc. These variations may have significant effect on path loss and thus network connectivity. On the other hand, there may be higher capacity static nodes available that can be used to enhance the network operation [3, 4]. These issues have been taken into consideration in the development of Kilavi building control platform.

Kilavi platform can be classified as a middleware. Middlewares are used to bridge the gap between the operating system (here sensors) and application, thus easing the application development. The purpose of a sensor network middleware is to hide the lower level qualities such as routing and channel access from the application and provide a communication platform to the application. Important sensor network middleware features are energy efficiency, reliability, security and scalability

Traditional distributed network middlewares such as CORBA and Jini are demanding in terms of computation and memory requirements. In sensor networks, there have been primarily distributed data-centric approaches. Cougar [5] and TAG [6] are simple SQL-type declarative interfaces for data dissemination and aggregation. SINA [7] also uses geographic clustering to enhance information aggregation. Smart Messages [8] is a user-defined platform based on agent-like messages. The Milan [9] enables dynamic networking with possibility of trade-offs between network quality of service and maximum lifetime.

The rest of the paper is organised as follows. Section 2 introduces Kilavi platform. Section 3 presents the basis to Kilavi evaluation and section 4 gives the results related to reliability and scalability of Kilavi. Finally, section 5 concludes the paper.

2 Kilavi platform

Kilavi platform can operate on different radios and it defines link and network layer characteristics and how the information is presented. These together provide the means for application development.

Kilavi platform utilizes higher capacity nodes and single high-resource management point to enhance and simplify sensor network operation and provide an interface to wireless and mobile control. Earlier work has indicated that Kilavi enables long lifetime for power critical sensor nodes, simplifies security architecture with end-to-end keys and provides low overhead network management [10-12]. Paper concentrates on reliability and scalability of Kilavi platform that can be used, for example, in Information Centre [13] system based applications, shown in figure 1.

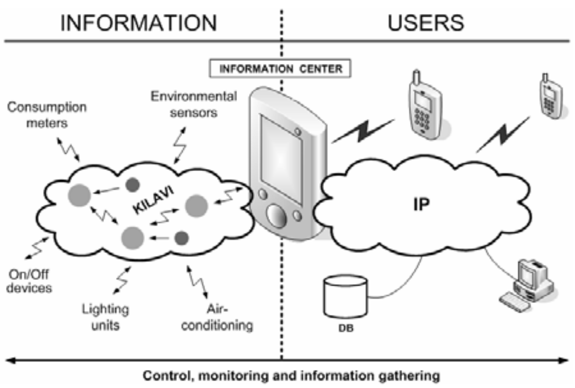

Fig. 1 Kilavi platform can operate as part of Information Centre architecture to gather information and relay control commands

Kilavi platform is intended for low-power and low data rate device control and monitoring. Kilavi offers an interface to all kinds of building control and measurement devices. It is comprehensive regarding to different functions needed building control, including dynamic network set-up and maintenance functions. Because Kilavi is targeted at building automation packet length, data rate, and functions can be optimized. Star topology is possible in Kilavi communication but with clustering and multihop, the intermediate nodes may be used to prolong sensor lifetimes, increase network size and enhance communication reliability in high path loss environment. Centralized master/slave architecture enables to concentrate resources and capabilities to network master. This enables the use of simple sensors, routing scheme and security procedure. Kilavi multihop network architecture is presented in figure 2. More Kilavi characteristics are presented in [10-12].

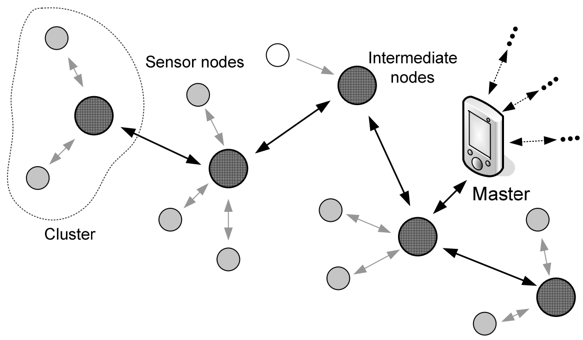

Fig. 2 Kilavi multihop cluster-tree architecture

Kilavi uses a hybrid flooding approach where route creation is similar to typical flooding. In flooding, maximum hop count is used and already flooded packets are ignored. After the initial flooding, created routes are used for future communication. Master is responsible of routing and it maintains a routing table that contains a route to every network node. Routes can be updated periodically or on-demand to guarantee network connectivity. Intermediate nodes (IN) forward messages based on the information included in every multihop packet, thus intermediates do not maintain any routing information. Route formation is depicted in figure 3.

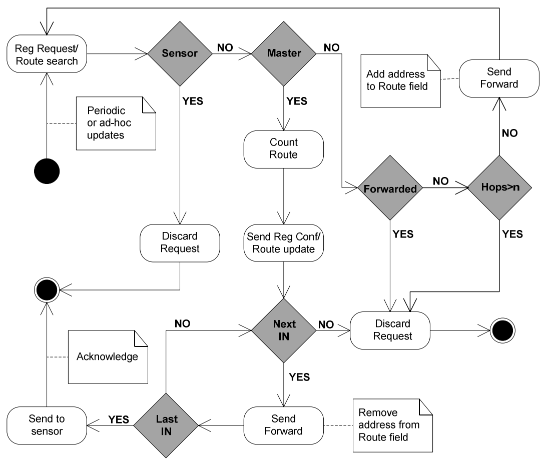

Fig. 3 Kilavi inter-cluster communication: route formation

In Kilavi, intermediates are used to enhance network range and lifetime of power scarce sensors. In multihop network, intermediates operate as master determined clusters-heads acting as short-term data storages. Sensors can periodically wake-up to query packets from cluster heads which decreases sensor node active time and thus power consumption. When sensors have data to send, they wake up and send it to the cluster head that forwards it further to the master on predetermined path. This type of operation is especially suitable for nodes that carry out periodic or sporadic measurements. Sensor operation in the cluster is depicted in figure 4.

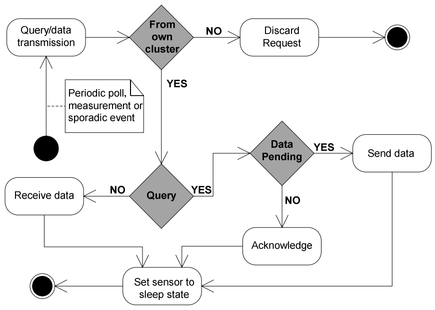

Fig. 4 Kilavi intra-cluster communication: data storing and polling

3 Basis for Kilavi evaluation

The simulation models are based on above-mentioned Kilavi networking principles. CSMA/CA method with RTS/CTS handshaking is used to provide the basis for reliable communication (channel is empty and receivers are ready), with reasonable packet overhead and power consumption. Thus it is used in following simulations.

The following simulations including star and cluster-tree networks test how the reliability of Kilavi platform varies in respect of different parameters. These parameters are related to radio (*data rate*: R and *modulation method*: M), network (*number of sensors:* N_S and *intermediates*: N_I, and *avg. hop count*: H), protocol (*packet length*: L), and traffic (data packet transmission interval). Simulation parameters are presented in table I.

TABLE I: Simulation parameters

Network types	Multi- and Single-hop
Data payload	0, 4, 8, 16, 32, 64 bytes
Modulation	BPSK, FSK, GMSK
Data TX interval	1, 6, 12, 30, 60, 120 / min.
Data rate	10, 25, 50, 100, 200 kbps
Hop count	1, 2, 3, 4, 5
Network size	5 to 129 nodes
Traffic type	Poisson
Carrier frequency	434 MHz
Transmission power	1 mW (0 dBm)

Simulations are executed with the OPNET Modeler/Wireless Module [14]. Simulated networks are presented in figure 5. In simulations, nodes in a cluster can hear traffic from all the adjacent clusters. In practise, this is achieved with Kilavi power control. Discrete probability Poisson traffic is used because nodes have no knowledge of other nodes' transmission schedules.

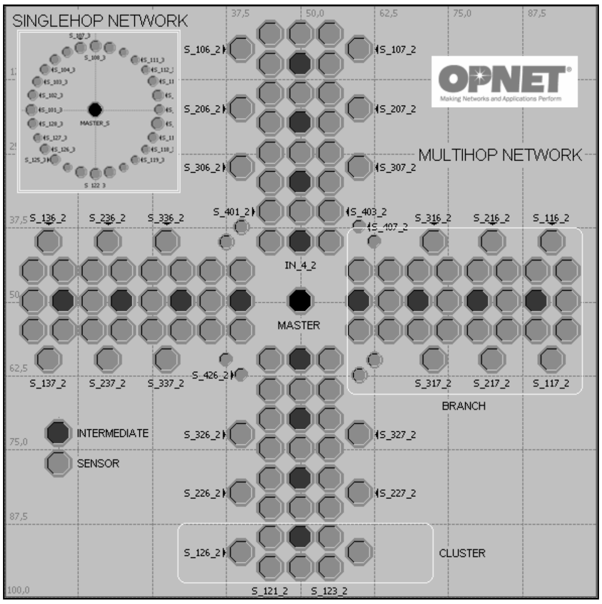

Fig. 5 Network models for Kilavi reliability and scalability simulations

4 Reliability and scalability

Kilavi network reliability and scalability issues are studied with following simulation scheme. Sensors are transmitting periodic measurements to intermediate nodes that forward them to the master node on pre-determined path. Master acknowledges successful transmissions by sending AVK to intermediate nodes aka cluster-heads which store these ACK messages. Sensors periodically query these cluster-heads and receive possible ACK messages. If sensor receives ACK related to initial transmission, the operation was successful. *1–packet loss* is used as a measure of end-to-end reliability.

4.1 CASE 1: Single hop Kilavi network

One of the main aspects of Kilavi has been short length packets that conserve power consumption and reduce collisions. Kilavi uses *KilaviA* packets to channel reservation (RTS/CTS) and to other control commands such as ACK. *KilaviB* packets are used for actual data transfer. In single-hop (SH) case, the length of *KilaviA* and *KilaviB* can be calculated with equation (1). Physical layer consists of 26 bits that are used for synchronization and CRC (Cyclic Redundancy Check) in Kilavi prototypes.

$$\begin{cases} L_{KILAVIA_{SH}} = L_{TX} + L_{RX} + L_{H} + L_{P} \\ L_{KILAVIB_{SH}} = L_{TX} + L_{RX} + L_{T} + L_{P} + L_{Data} \end{cases} \quad (1)$$

Transmitter address (L_{TX}) = 16 bits
Receiver address (L_{RX}) = 16 bits
Message header (L_H) = 16 bits
Message type (L_T) = 8 bits
Physical layer (L_P) = 26 bits
Data payload (L_{Data}) = *X* bits

At first, the influence of network size to communication reliability is tested. In single-hop case there are 4 to 28 sensor nodes and the master node in the network. Figure 6 shows that when the network traffic rate is under 5 packets per minute per node, 95% reliability is achieved with 28 sensor nodes, 98% with 12 sensor nodes, and 100% with fewer than 8 nodes.

If traffic rate is increased to 30pkts/min/node, reliability decreases considerably as network size increases; 4 nodes (98%), 12 nodes (92%), and 28 nodes (67%). 12 sensor node network has fair amount of packet losses and thus it has been used in the rest of the single-hop simulations.

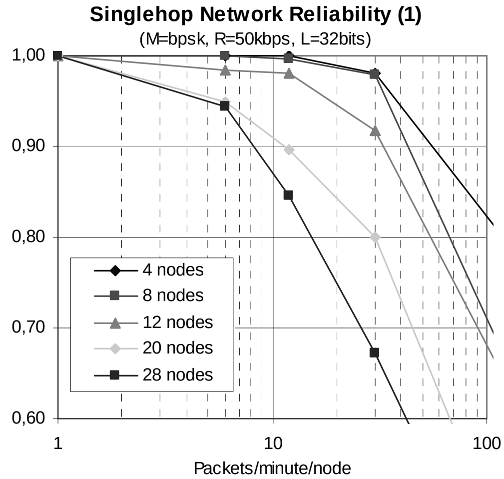

Fig. 6 Single-hop: network size vs. reliability

Next, the packet size effect is simulated by increasing the length of *KilaviB* payload. Figure 7 indicates that when traffic rate is under 5pkts/min/node, packet size has no significant effect on reliability. When traffic rate is raised to 30pkts/min/node, the reliability of a 12-node network improves from 90% to 94% as data payload decreases from 512 to 32 bits. Thus, packet size has an effect to reliability.

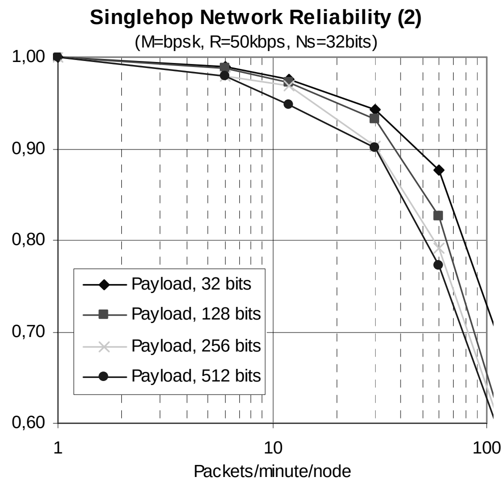

Fig. 7 Single-hop: payload length vs. reliability

Modulation used in Kilavi prototypes is simple BPSK (Binary Phase Shift Keying). Next, the effect of GMSK (Gaussian minimum shift keying), FSK (Frequency Shift Keying) and BPSK modulation methods are tested to Kilavi reliability. Figure 8 shows that in low traffic there are no significant differences between these methods. However, when traffic rate is increased to 30pkts/min/node, the reliability is 90% with FSK, 95% with GMSK and 97% with BPSK. Thus, used modulation proved to be effective.

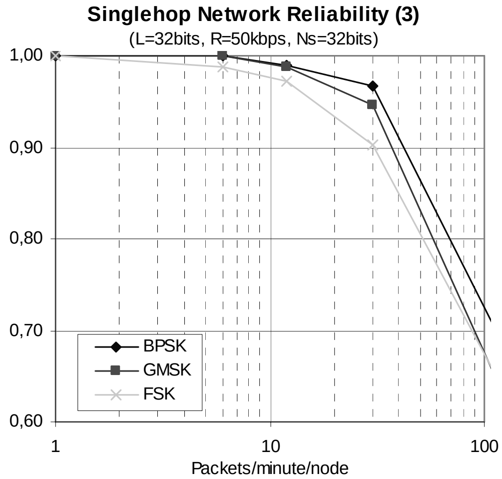

Fig. 8 Single-hop: modulation vs. reliability

Data rate simulations show that when traffic rate is 30pkts/min/node, the reliability improves from 80% to 97% as the data rate increases from 10 to 50kbps (M=BPSK, L=32bits, N_S=12). Simulations indicate, however, that data rates over 50kbps improve the reliability only marginally even when traffic rate is over 30pkts/min/node.

4.2 CASE 2: Multihop Kilavi network

Multihop communication is important to increase the network size and enhance the operability of Kilavi platform. At first, the simulations study the packet size effect on the network reliability. Network includes 28 sensor nodes and 4 intermediate nodes and the master.

In multihop case (MH), route information is included to *KilaviB* packets. Intermediates eliminate their own addresses from the route field of *KilaviB* packet thus shortening the packet size by 16-bits per hop until it arrives to the destination. The average length of *KilaviB* packet can be calculated with equation (2), where *n* is the hop count.

$$\begin{cases} L_{KILAVIA_{MH}} = L_{KILAVIA_{SH}} \\ L_{KILAVIB_{MH}} = L_{KILAVIB_{SH}} + 16 \cdot \sum_{i=1}^{n} (n-i) \cdot \frac{1}{n} \end{cases} \quad (2)$$

Figure 9 indicates that when traffic rate is under 5pkts/min/node, over 98% reliability is achieved with all simulated packet sizes. When traffic rate is raised to 30pkts/min/node network reliability decreases from 96% to 87%, as the payload size increases from 32 to 512 bits. Thus, even in a small network, the payload size has a strong effect on packet losses.

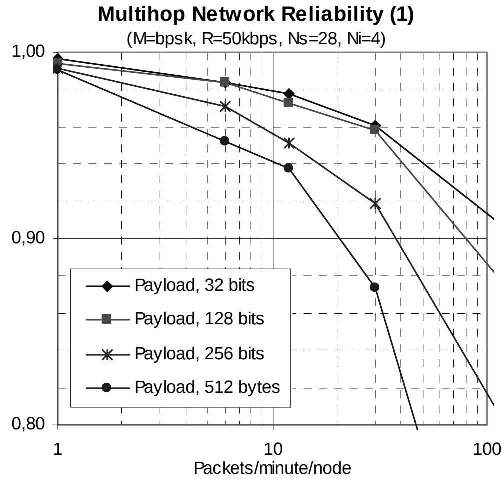

Fig. 9 Multihop: payload length vs. reliability

Next, the data rate effect is studied with same network topology. Figure 10 indicates that when traffic rate is under 5pkts/min/node, there is only 2 percentage unit difference in reliability between data rates from 10 to 100kbps. When traffic rate is increased to 30pkts/min/node, the reliability improves from 83% to 96% as the data rate is raised from 10kbps to 50kbps. Data rates over 50kbps do not improve reliability, except in very high traffic rate (over 60pkts/min/node) scenarios.

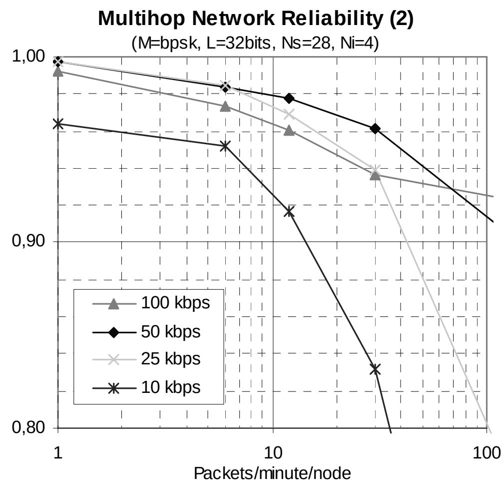

Fig. 10 Multihop: data rate vs. reliability

Next, the reliability of Kilavi platform in larger networks is studied which also indicates Kilavi scalability. In other words, the influence of cluster sizes and branch numbers to network reliability are studied. Results will indicate, particularly, how the network master and intermediates can handle the additional traffic.

Figure 11 shows simulation results from a setup that contains 4 network branches with 4 adjacent clusters, every cluster having 1 to 7 sensors (see Fig 5). Thus the network includes the master, 16 intermediate nodes and 16 to 112 sensor nodes. The goal is to study the effect of cluster size on reliability. Results show that when data traffic rate is 12pkts/min/node, reliability is 98-100%; when data traffic rate is 30pkts/min/node, reliability is 93-97%; and when data traffic rate is 60pkts/min/node, reliability is 85-94%, depending on the cluster size.

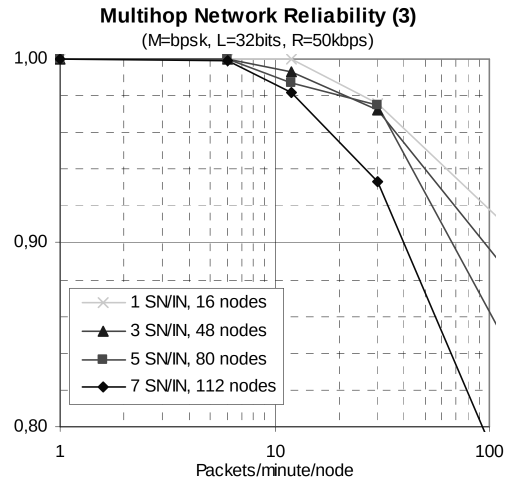

Fig. 11 Multihop: cluster size vs. reliability

Figure 12 shows results from a setup that contains the master node and 1-4 branches all including 4 intermediates and 28 sensor nodes. This case studies the effect of branch number to Kilavi network reliability. Results show that, when data traffic rate is 12pkts/min/node, reliability is 97-99%; when data traffic rate 30pkts/min/node, reliability is 93-97%; and when data traffic rate is 60pkts/min/node, reliability is 85-92%, depending on the branch count (1 to 4). Thus network scales well to larger networks, when traffic is reasonable.

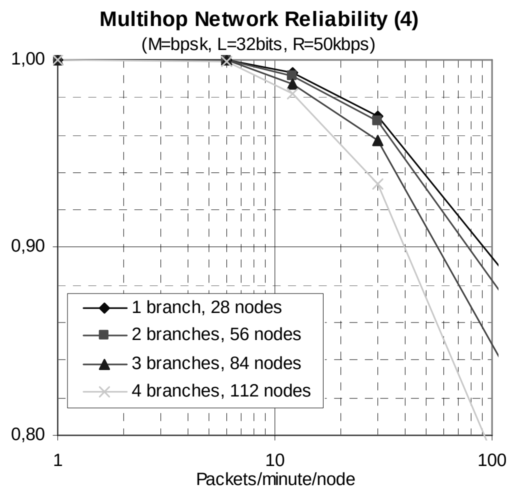

Fig. 12 Multihop: branch count vs. reliability

Finally, figure 13 summarizes that multihop helps to achieve a more reliable Kilavi networking. It also indicates that when having 28 sensors and 4 intermediates, the most reliable network topology is cluster-tree having only one branch. However in this case, there is higher risk of communication failure because of the high dependency on the intermediate node closest to the root.

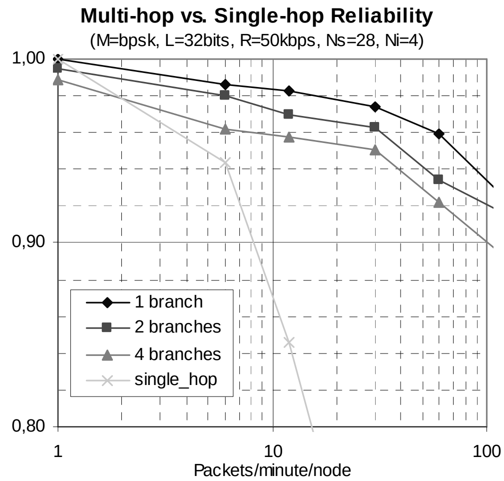

Fig. 13 Multihop vs. single-hop reliability and multihop topology influence to reliability

5 Conclusions

Simulations indicated that single-hop Kilavi has quite limited sensor capacity. However, when packets are sent very infrequently, a sufficient level of reliability can be achieved, even with larger numbers of sensor nodes. Large range networks are hard to implement in a high path loss building environment with single-hop because higher transmission power would cause extra power consumption and decrease reliability because of increased network interference. Also, packet length has major contribution to network reliability and to the amount of nodes network can handle.

Multi-hop simulations showed that the reliability of Kilavi platform can be enhanced by clustering and using intermediates to forward data between sensors and the network central node. The packet size has a cumulative effect to network operation and thus it is even more important to have short packets to achieve reliability. It can also be seen that data rates over 50kbps are not increasing network reliability in studied scheme. The important result is that Kilavi may be successfully employed in a network of over 100 sensors, though centralized sensor network is not generally speaking as scalable as a distributed ones.

To summarize, the application layer traffic optimization will generally determine sensor network reliability and scalability. Simulations showed that the implementation of multihop wireless Kilavi building automation platform is feasible. Thus, the future studies will concentrate on the practical implementation of large scale Kilavi network.

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